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FEASIBILITY STUDY FOR A THREE-LEGGED MOBILE PLATFORM

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FEASIBILITY OF A THREE-LEGGED MOBILE PLATFORM

INTRODUCTION

This paper will discuss the results of a Phase I study of a three-legged transportation vehicle named SKITTER. The pupose of this vehicle is to serve as a transportation device for the lunar surface for a variety of scientific and construction attachments. While the scope of this feasiblity study only encompasses Lunar applications, SKITTER itself is not limited to the moon. Applications on Earth and other planets will be discussed later.

The design of a transportation vehicle for Lunar applications must meet many more design constraints than its terrestrial counterparts. First, it must be extremely simple. This means it must have as few moving parts as possible so as to reduce the areas that can fail. Secondly, the parts that do move must be very reliable. This is an obvious fact that has not been considered early enough in the design process before this time. We have sought to show that this device can accomplish the mission of moving a payload from point A to point B in a reliable, safe manner. This will reduce the need for expensive and dangerous EVA by the astronuats on the Lunar surface.

This paper seeks to analyze the dynamics and controls necessary for this device. Mathmatical models will be derived and a control law developed to demonstrate the basic motions possible for this device. These models will then be incorporated into a computer simulation of a hydraulic system (chosen for simplicity - the actual system chosen will be determined later). This allows the designer to identify and vary the critical parameters to optimize the design under the restrictions of the machanical and physical system. The feasiblity of this device will then be discussed with the results from the program (velocities, accelerations, forces, moments, flow rates, and horse power) as the key elements.

PROBLEM STATEMENT

The purpose of this project was to determine the feasibility of a three-legged walker called SKITTER. The initial idea and conceptual work was done by Mr. J. W. Brazell of the Georgia Institute of Technology. This paper tries to clarify his ideas and put them together into a concrete design that could meet the design objectives for such a device. The scope of this project was limited to developing the mathmatical models that govern the two most critical areas - the dynamics and controls. Based on the results of the analysis, suggestions and conclusions will be drawn about the future of SKITTER.

MOTION

Mechanical simplicity was a primary design constraint for SKITTER. Although other walkers incorporate complex linkages and bearings in their design, SKITTER utilizes only six linear actuators (2 per leg) and three hinges (1 per leg) to generate motion (fig. 1, View A-A). The Extender actuator at the bottom of each leg changes the leg length while the Swing actuator changes the angular position of the leg relative to the body. By coordination of these actuators, a variety of positions can be achieved giving SKITTER a distinct advantage over some current mobile platform designs.

Lean

One basic motion SKITTER can perform is to shift its CG to a new position or to "lean". Starting with SKITTER at some equilibrium position (fig. 2), Leg 1 can be extended causing SKITTER to rotate about the Pivot Line (fig. 1) which changes the position of the CG. By coordinating the actions of all six actuators, SKITTER could achieve a variety of configurations which would be useful for such applications as zeroing in on targets for Lunar surveying and drilling operations.

Squat

SKITTER could lower its CG or "squat" by a series of coordinated movement of the actuators. Leg 1 could extend or lean SKITTER. The Extender actuator would then retract from the surface causing SKITTER to become unstable and rotate backwards about the Pivot Line. While Leg 1 is not contacting the surface, the Swing actuator would rotate the leg away from the body. Finally, Leg 1 would contact the surface and SKITTER would once more be stable; however, its CG would be lower than at the equilibrium position. Each leg would follow the same sequence until the CG was at a suitable position. If the the sequence is carried through enough iterations, the body of SKITTER would come to rest on the surface with the legs extended from the body (fig. 3). In this position the legs could act as out-riggers for a Lunar lifting device such as a crane.

Crutch Walk

By choreographing the previous motions, SKITTER would be able to traverse distances over varied terrains. Starting again at some equilibrium position (fig. 4), SKITTER would lean in the direction of travel by extending Leg 1. The Extender actuator would retract while the Swing actuator

CRUTCH WALK

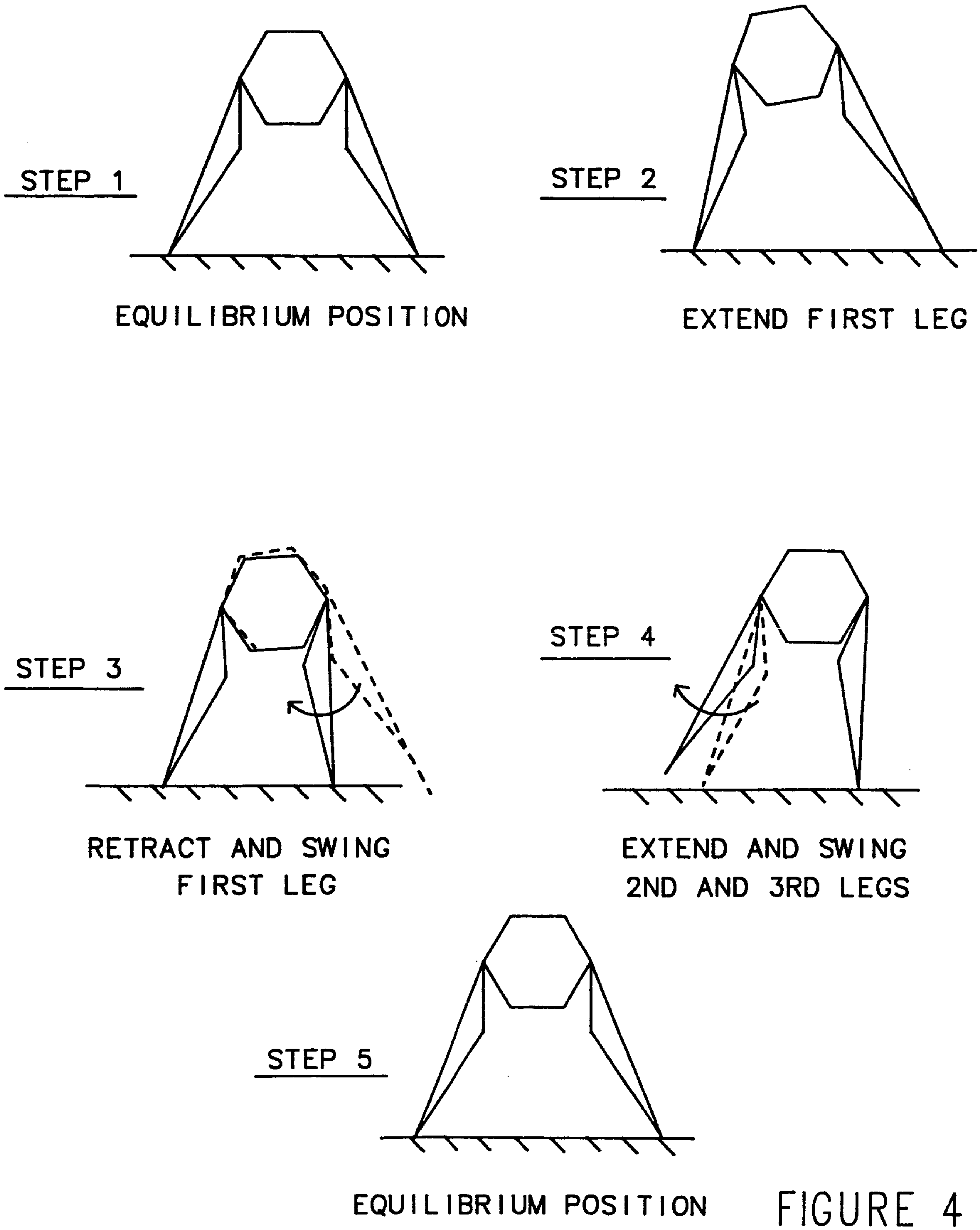
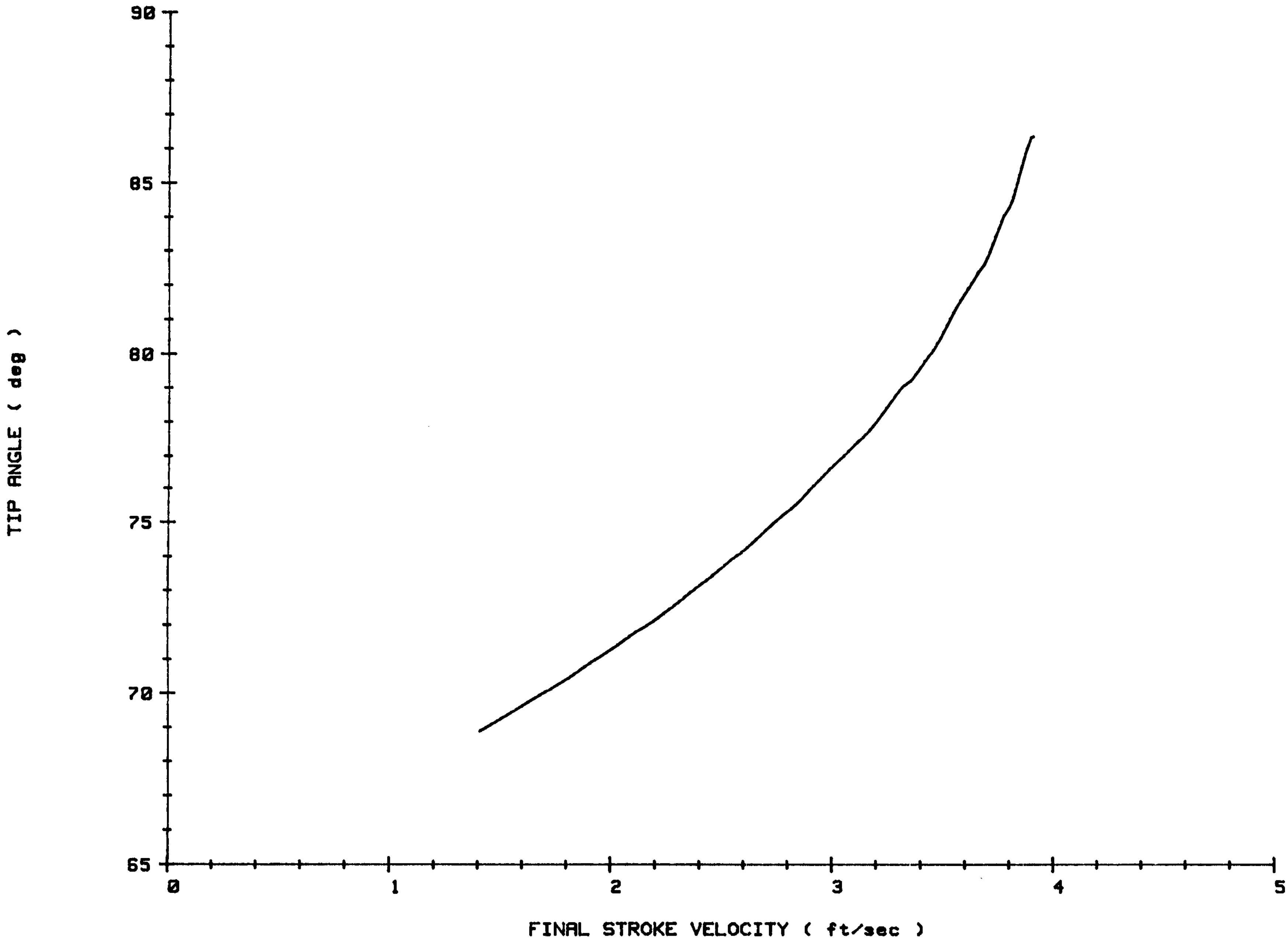


FIGURE 4

TIP ANGLE vs. FINAL STROKE VELOCITY
FIGURE 6



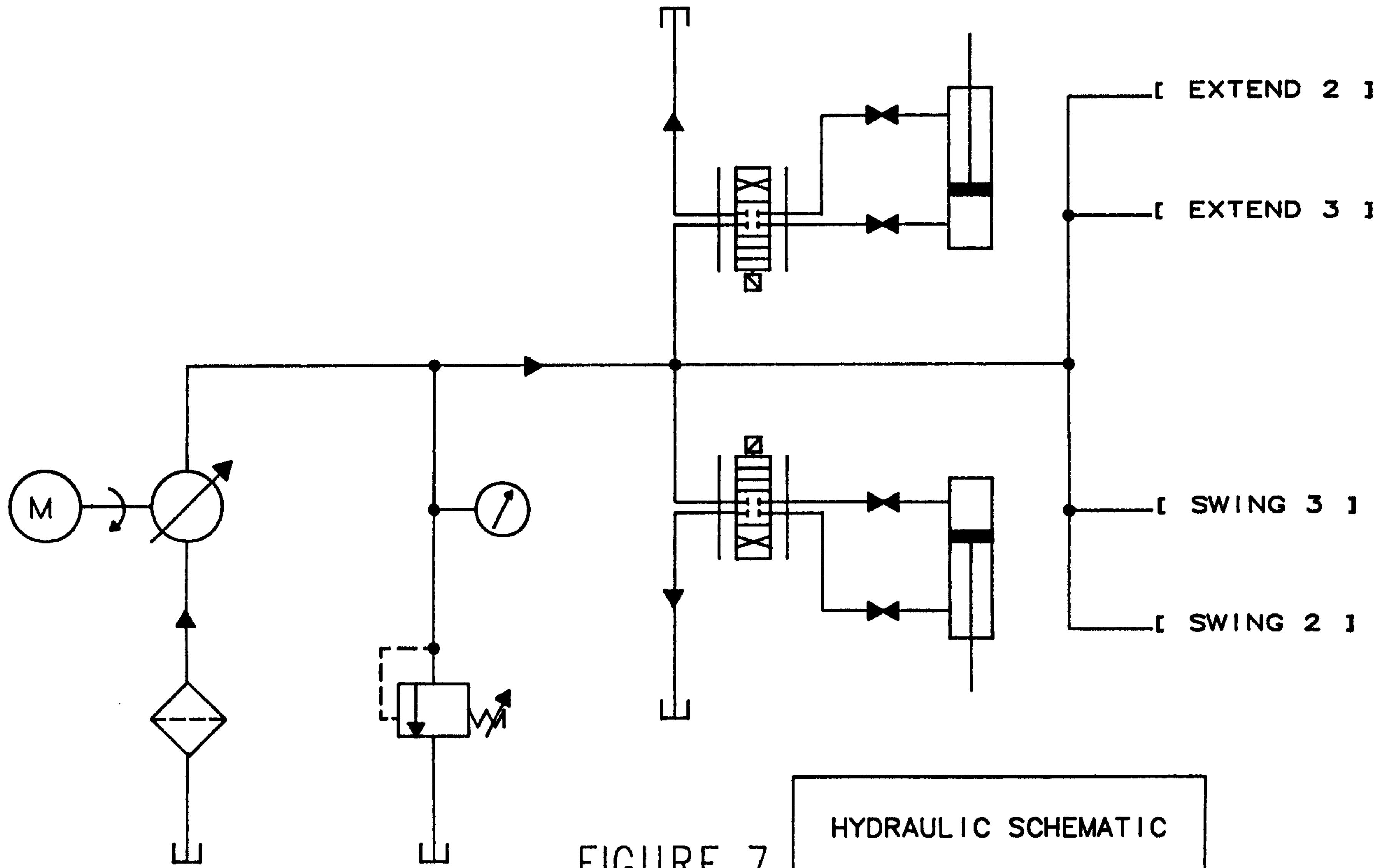
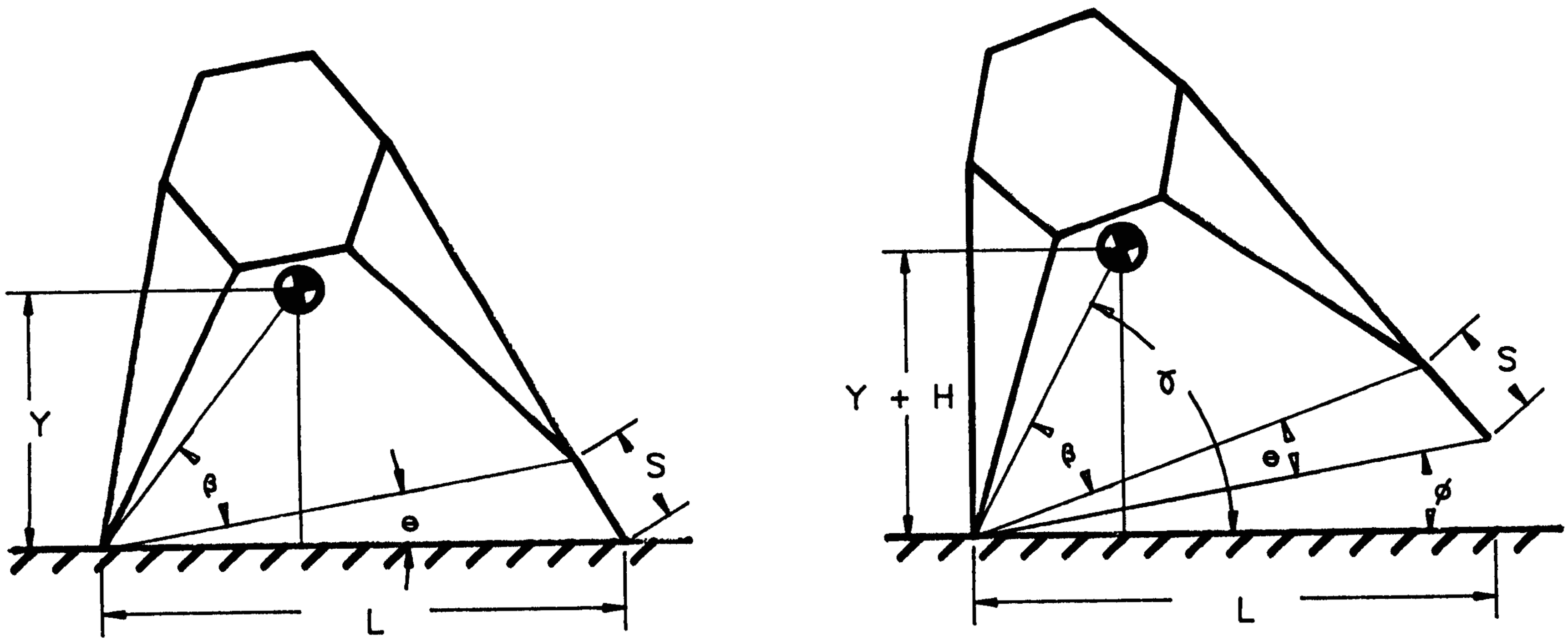


FIGURE 7

HYDRAULIC SCHEMATIC
MOBILE PLATFORM

SKITTER DYNAMICS



DURING STROKE   FIGURE 5   AFTER STROKE would simultaneously swing Leg 1 toward the body. As Leg 1 contacts the surface, it is at a new position. Leg 2 and Leg 3 would extend, retract, and swing away from the body. SKITTER is again at a equilibrium position; however it has translated. By using the inertia of SKITTER and a proper initial force, a rocking motion could be achieved to translate the CG. The horse power to maintain the rocking motion would be small since the energy input to the system after the rocking motion is established would only have to account for the losses in the system due to SKITTER contacting the surface.

Leap

One method for maneuvering around obstacles which might impair the movement of SKITTER such as small rocks or ditches is to "leap" over them. With SKITTER leaning in the direction of travel, all three Extender actuators could fire with sufficient force to make SKITTER leap. With increasing control logic and proper frame design, the magnitude of the leap could increase giving SKITTER the abilty to achieve larger distances.

The movements just discussed were achieved by utilzing the inertia charateristics of SKITTER in conjunction with the coordinated actions of the six linear actuators. A direct relation between movement complexity and control complexity is apparent; however, the movements discussed could be realized by current control strategies and devices.

DYNAMICS

Introduction

This section will deal with the governing equations of motion for SKITTER. The assumptions for this analysis were that SKITTER had a mass value of 340 lbm. and a distribution of one-half of the mass in the body while the remaining mass was equally distributed between the three legs. From these assumptions and the geometry of the walker, the location of the center of mass and a moment of inertia for SKITTER were calculated.

The attached program, SKIT CONTROLS, performs the calculations that will be discussed in the following sections. The equations will be discussed now and the sample calculations will be discussed in a later section. All notation with the subscripts i, i+1, ect. refer to a instant in time in which the value is occuring.

CENTER OF MASS AND MOMENT OF INERTIA

Introduction

Before the dynamic analysis of SKITTER could carried through, it was first necessary to calculate the basic physical properties. Thus, the center of mass for each leg and the body was calculated along with its volume and then a center of mass and moment of inertia for SKITTER as a whole were arrived at.

Center of Mass

These calculations are based upon the triangular shape of the leg. Each leg was first divided into two smaller volumes and a center of mass for each of these volumes was calculated. Then, a volume was found thru the integration of the area over a length while maintaining the decreasing triangular shape. In this way, a table was generated for each structure of its center of mass and volume. These values were then combined with the values for the body of SKITTER, which was assumed to be spherical for the purposes of this first study. The results of this analysis are in Table . The derivation has been included in the appendix for completeness of this analysis.

Moment of Inertia

A moment of inertia was calculated by using the standard equation for moment of inertia about the center of mass:

$$I = \Sigma M_I \times R_I^2$$

This value was easily calculated using Table 1.

DYNAMICS EQUATIONS

The movement of SKITTER can be broken into 3 distinct stages beginning from the equilibrium position:

1) Actuator begins to move causing SKITTER to rotate about the contact axis formed by the other 2 legs. This phase is characterized by a constant acceleration over the entire stroke length.

2) SKITTER rotates off the ground and is subject to the lunar gravity. It is critical at this stage that the angle the center of mass makes to the ground, known as the Tip Angle, does not exceed 90 degrees or else SKITTER will tip over.

3) SKITTER rotates back to the ground with the leg having rotated in 20 degrees into a perpendicular position,

thus arriving at a new position.

Because of the nature of the problem, we have modeled the system as a body undergoing rotation about the contact axis. A diagram of the body with the notation that is to be used is included at the back in Fig. 5 for ease of understanding of the equations to follow.

Stage 1

In this stage, the control system varies the force from the hydraulic system to maintain a constant linear acceleration for the entire stroke length. The acceleration is calculated by the formula :

$$\mathrm{ACCELERATION}_{I+1} = \frac{V_{CYLINDER,I+1} - V_{CYLINDER,I}}{\Delta T}$$

Since the force is always tangent to the circular path that the leg follows, this acceleration is a tangential acceleration. Thus, the angular acceleration is calculated:

$$\alpha_{I+1} = \frac{\mathrm{ACCELERATION}_{I+1}}{L}$$

This angular acceleration will hold constant for the time between the sampling of the control system. Therefore, the angular velocity is calculated from the previous alpha:

$$\omega_{I+1} = \omega_I + \alpha_I \times \Delta T$$

The angle of rotation, Theta, is to be calculated based on the same idea that this angular acceleration and velocity will hold constant over the sampling time.

$$\theta_{I+1} = \theta_I + \omega_I \times \Delta T + \frac{\alpha_I \times \Delta T^2}{2}$$

Now that a desired angular acceleration has been calculated to maintain a constant linear acceleration, the force required to generate that acceleration is to be calculated. Since we are dealing with a system that is rotating, we use the angular momentum equation to calculate this force. This basic equation is:

$$I_A \times \alpha = \Sigma R \times F$$

When one examines the force balance, there are 3 forces that need to be considered in the moment equation. The first force, the weight of SKITTER, has a variable moment arm as it rotates about the Pivot Line. The other 2 forces, the reaction force at the leg and the force being generated to make SKITTER rotate, have a constant moment arm since they maintain contact with the ground. Thus after some algebraic manipulation, the equation becomes:

$$F = \frac{I_A \times \alpha + M \times G(D \times \cos(\theta + \beta) - \frac{L}{3})}{L \times \cos(\theta)}$$

The cos(Theta) term in the denominator is due to the fact that the force's component in the y-direction varies as the body rotates.

Stage 2

This part of the motion is when SKITTER continues to rotate due its inertia properties. It is during this time that the actuator retracts to its normal state. Since the critical parameter as to whether SKITTER will tip over or not is the Tip Angle, this is the parameter that is calculated in the program. The derivation of the angle that the center of mass will be at when SKITTER stops rotating is based on the height that the center of mass has changed during its rotation. Thus, from the conservation of energy which says:

$$PE_1 + KE_1 = PE_2 + KE_2$$

and knowing that:

$$\Delta KE = W = \int F \cdot dR$$

We are able to calculate the height of the center of mass by letting point 1 in the above equations to be the point that the force stops and point 2 be the point that the body stops rotating. Thus :

$$PE_1 = M \times G \times COS(\theta)$$

Where the zero state, or datum, is the static equilibrium position. Thus, in our program, we calculate as average force over the time the stroke acts and multiply that by Theta to get the work done over the stroke length. With this now calculated, the change in height of the center of mass is known and thus its angular position is known from:

$$\gamma = SIN^{-1}\left(\frac{Y+H}{(X^2+Y^2)^{\frac{1}{2}}} \right)$$

Refer to Fig. 6 for a plot of the Tip Angle versus the final stroke velocity. This final stroke velocity is directly related to the acceleration that the control system is controling to.

Stage 3

This phase is characterized by the rotation of the leg in 20 degrees and allowing SKITTER to fall back to a new static position. Since there are no forces acting on SKITTER except for gravity, the conservation of energy theory easily can be applied to determine the critical angle of rotation necessary to give enough time and height to allow the leg to swing to its new position. Since the swinging motion is not restrained to constant acceleration, the system can perform this operation in not more than .015 seconds. The swing maneuover will only be performed during its downward motion so as to prevent its motion from creating a force that might aid the tipping over of SKITTER. Using this time of .015 seconds as the critical time, the angle of rotation that will give this time before it reaches its new static position will be derived.

First, a velocity in the y-direction is calculated for SKITTER if it is to fall for .015 seconds. Since the initial velocity is zero,

$$V = G \times T = .0822 \frac{FT}{S}$$

From the conservation of energy equation with the PE at 2 and the KE at 1 equal to zero, this gives:

$$M \times G \times (Y_{2,CM} - Y_{1,CM}) = \frac{M \times V^2}{2}$$

Thus, the change in Y from the fall equals .0011 feet. The final height of the center of mass will equal the height of the center of mass plus the change due to the swing of the leg:

$$Y_{2,CM} = Y + \frac{\text{LEG HEIGHT}}{\cos(2\emptyset)} - \text{LEG HEIGHT} = 16.425 \text{ FT}$$

Thus, the height at the point SKITTER begins to fall back to the moon is 16.43 feet. This means that the tip angle at this critical time is equal to 73.35 degrees. Thus, as long as the rotation exceeds this value, the swing maneuver can be completed.

POWER SYSTEM

SKITTER's motion is a coordination of movement by six linear actuators as outlined in the motion section. These linear actuators can be either electro-mechanical power screws or hydraulic in nature. Due to the vast experience of the advisor and for simplicity sake, a hydraulic power system was chosen.

Hydraulic Schematic

The proposed system is a hydraulic demand flow network. A variable flow pump is used to supply the system while a relief valve keeps the system pressure at 3000 psi maximum. Each actuator is controled by a servo valve and monitored by a position sensor (Fig. 7).

Hydraulic Equations

Since a hydralic power system was chosen, the governing equations involving flow (Q), the pressure differential (delta p), cylinder bore area (Ab), and the horse power (hp) could be utilized in the control simulation of the linear actuator.

These equations include:

Force = Ab * Delta P

Q = Ab * Velocity

HP = (Delta P * Q) / 1714

CONTROLS

Introduction

Although the SKITTER is being designed with mechanical simplicity in mind, the control logic complexity is directly proportional to the complexity of motion. For the basis of establishing a simple translatory motion as defined earlier by the "crutch walk" gait, a theoretical control system was designed which will be used as a take off point for Phase II developement of SKITTER.

System Control

The proposed method for controling the motion of SKITTER is based upon a "Master - Slave" relationship between controlling devices (fig. 8). The slaves are dedicated microprocessors with the control logic to monitor the actuators they are responsible for. There are two types of Slave devices, Swing Slaves and Extender Slaves, which have corresponding control logic. For redundency, the members of each slave type are networked so that in the event of a slave failure, the actuator may be monitored by another slave on the network.

The Master would monitor the status and coordinate the action of each slave as well as monitor platform variables, such as Tip Angle. The Master could be a human operater who is at a control panel throwing switches to obtain elemental movement of the actuators. Also a small computer, such as the Hewelet-Packard HP-71 could be programed to act as the System Master, and further into the future, SKITTER could incorporate artificial intelligence logic and evolve into a "smart platform".

Actuator Control

The individual control logic for each actuator is based on closed-loop velocity feedback (Fig. 9). From a sensor (accelerometer or position sensor), the velocity at the current actuator position is determined. The actuator slave compares the velocity with the prescribed velocity for that position. An error signal results and is conditioned by the gain. This new error signal is sent from the slave to the plant devices (servo valve and cylinder for a hydraulic system) which results in a new position. The cycle is then reiterated and the actuator motion converges to the predescribed motion that is input by the user.

Control Simulation

The program, Skit Control, simulates the motion of leg 1's extender actuator based on a hydraulic system, for the "crutch walk" motion. The first leg's extender actuator was simulated since its movement is more complex (extending such that it will not tip SKITTER over) as compared to the swing actuators which just fire to rotate the legs in and out as fast as they can. The user inputs an initial force, a gain k, and a acceleration which is the slope of the velocity profile that the actuator should follow. The program

The gain k was arrived at through experimentation until a stable system was experienced. By optimizing the gain, a faster convergence would be achieved.

APPLICATIONS

The applications for this device are as wide and diverse as the locations for which we foresee its uses. From the construction and scientific applications on the lunar surface, to mobile probes on other planets, to hazardous environments on earth, this device can be used.

The reason for the wide range of uses is in the inherent simplicity of the design. Since it requires only six actuators and no mechanical power transmission system, SKITTER is ideal for use in any area where reliability is of extreme importance. Since this device is able to squat and adjust its height, it is flexible in the volume of the workspace needed for it to operate in.

On the lunar surface, SKITTER can be used as a transportation device for any materials and serve as a host to a number of scientific and construction implements such as drills, cranes, robotic arms, probes, etc. While on the surface of another planet, SKITTER would provide a reliable system to land on the surface and then move about to explore what is just over the horizon. Here on earth, it can carry probes and sensors into environments that have been potentially filled with dangerous gases and report its findings, it can also transport away dangerous materials, such as explosives and radioactive materials, and go wherever man can not safely go.

CONCLUSIONS

At this time, we do not feel that there are any reasons that the SKITTER project should not be continued into Phase II - construction of a working model. While optimization of some of the critical parameters - such as the height of the center of mass to leglength ratio and the strokelength - is still to be completed, the mathematical models have been developed for this type of analysis.

Additional attention will be paid to such areas as the mass characteristics, since a number of assumptions were made and more realistic numbers are needed. The controls scheme needs to expand to encompass a number of small negative effects such as transfer functions for the cylinder and the servo valve as well as a time delay in the control system. These are not critical factors to the decision to continue this project, but they will play large roles when the design is to be optimized in the following quarters.

```
PROGRAM SKIT CONTROLS

IMPORT SYSDEVS;

CONST
   LUNAR_GRAV   = 5.479;
   PI           = 3.1415926;

VAR
   HPVST               : TEXT;
   FVST                : TEXT;
   PVST                : TEXT;
   VVST                : TEXT;
   AVST                : TEXT;
   TIME                : REAL;
   VELOCITY_COMP_NOW   : REAL;
   ERROR               : REAL;
   DELTA_FLOW          : REAL;
   FLOW                : REAL;
   GAIN_K              : REAL;
   BORE_AREA           : REAL;
   VEL_CYL_2           : REAL;
   FORCE               : REAL;
```

```
FORCE_AVG          : REAL;
VEL_CYL_1          : REAL;
MASS               : REAL;
ALPHA              : REAL;
OMEGA              : REAL;
THETA              : REAL;
LEGLENGTH          : REAL;
I_ABOUT_A          : REAL;
I_CM               : REAL;
Y                  : REAL;
Y1                 : REAL;
X                  : REAL;
ACCELERATION_CM    : REAL;
ACCELERATION_L     : REAL;
XBAR               : REAL;
YBAR               : REAL;
A_TO_CM_XY         : REAL;
A_TO_CM            : REAL;
SLOPE              : REAL;
INIT_ANGLE_CM      : REAL;
ANGLE_F_STOPS      : REAL;
STROKE             : REAL;
PRESSURE           : REAL;
HORSE_POWER        : REAL;
TOTAL_TIME         : REAL;
Y_AFTER_F_CM       : REAL;
```

```
    VELOCITY_CM          : REAL;
    DELTA_Y_AFTER_F_CM   : REAL;
    ANGLE_AFTER_F        : REAL;
    TOTAL_ANGLE_ROTATED  : REAL;
    CM_ANGULAR_POSITION  : REAL;
    COUNT                : INTEGER;
    RUN_AGAIN            : BOOLEAN;
    BUFFER               : CHAR;


PROCEDURE INITVAR;

    BEGIN
    KEYBUFOPS( KCLEAR , BUFFER );
    COUNT := 0;
    I_ABOUT_A := 21755.0794;
    STROKE := 2.0;
    LEGLENGTH := 23.425 + 2.0 * COS( 20.0 * PI / 180.0 );
    MASS := 62.15;
    XBAR := LEGLENGTH / 3.0;
    YBAR := 15.264;
    BORE_AREA := 0.2666667;
    THETA := 0.0;
    OMEGA   := 0.0;
    BUFFER := 'A';
    TOTAL_TIME := 0.0;
```

```
TIME := 0.0100;
VEL_CYL_1 := 0.0;
VELOCITY_COMP_NOW := 0.0;

WRITELN( OUTPUT, 'INPUT GAIN = ?' );
READ( INPUT, GAIN_K );
IF GAIN_K > 2.0 THEN
   HALT;

WRITELN( OUTPUT, 'INPUT INITIAL FORCE = ?' );
READLN( INPUT, FORCE );
IF FORCE > 9998 THEN
   HALT;

WRITELN( OUTPUT, 'INPUT DESIRED ACCELERATION AT LEG = ?' );
READLN( INPUT, SLOPE );

FORCE_AVG := FORCE + MASS * LUNAR_GRAV / 3.0;
A_TO_CM_XY := SQRT( SQR( XBAR ) + SQR( YBAR ));
A_TO_CM := SQRT( SQR( A_TO_CM_XY ) + SQR( LEGLENGTH ) / 4.0 );
INIT_ANGLE_CM := ARCTAN( YBAR/XBAR );
ACCELERATION_CM := FORCE / MASS;
ALPHA := ACCELERATION_CM / A_TO_CM_XY;
ACCELERATION_L := ALPHA * LEGLENGTH;
FLOW := VEL_CYL_1  * BORE_AREA;
ANGLE_F_STOPS := ARCTAN( STROKE * ( 1.0 - SQR( STROKE )/
```

```
                  ( 4.0 * SQR( LEGLENGTH ))) / ( LEGLENGTH
                  - SQR( STROKE ) / ( 2 * LEGLENGTH )));
   I_CM := I_ABOUT_A - MASS * SQR( A_TO_CM_XY )

   END;


PROCEDURE STAGE_1;

   BEGIN

   WHILE THETA < ANGLE_F_STOPS DO
      BEGIN
      TOTAL_TIME := TOTAL_TIME + TIME;
      VELOCITY_COMP_NOW := SLOPE * TIME + VELOCITY_COMP_NOW;
      ERROR := VELOCITY_COMP_NOW - VEL_CYL_1;
      DELTA_FLOW := ERROR * GAIN_K;
      FLOW := FLOW + DELTA_FLOW;
      VEL_CYL_2 := FLOW / BORE_AREA;
      ACCELERATION_L := ( VEL_CYL_2 - VEL_CYL_1 ) / TIME;
      VEL_CYL_1 := VEL_CYL_2 ;
      THETA := THETA + OMEGA * TIME + ALPHA * SQR( TIME ) / 2.0;
      OMEGA := OMEGA + ALPHA * TIME;
      ALPHA := ACCELERATION_L / LEGLENGTH;
      FORCE := ( I_ABOUT_A * ALPHA + MASS * LUNAR_GRAV *
               ( -1.0 * XBAR * COS( THETA + 20.0 * PI / 180.0 )
```

```
        + A_TO_CM_XY * COS( THETA + INIT_ANGLE_CM )
        )) / ( LEGLENGTH * COS( THETA ));
FORCE_AVG := FORCE_AVG + FORCE + MASS * LUNAR_GRAV / 3.0;

PRESSURE := FORCE / BORE_AREA;
HORSE_POWER := PRESSURE * FLOW / 1714.0;

IF COUNT > 10 THEN
  BEGIN
  WRITELN( OUTPUT, 'GAIN = ', GAIN_K );
  WRITELN( OUTPUT,'FORCE= ',FORCE);
  WRITELN( OUTPUT, 'ALPHA = ', ALPHA );
  WRITELN( OUTPUT, 'ACCELERATION AT L = ', ACCELERATION_L );
  WRITELN( OUTPUT, 'THETA = ', THETA*180/PI );
  WRITELN( OUTPUT, 'ERROR = ',ERROR );
  WRITELN( OUTPUT, 'VELOCITY = ', VEL_CYL_2  );
  WRITELN( OUTPUT, 'FLOW = ', FLOW );
  WRITELN( OUTPUT, 'PRESSURE = ', PRESSURE );
  WRITELN( OUTPUT, 'HORSE POWER = ', HORSE_POWER );
  WRITELN;
  (* WRITELN( HPVST, TOTAL_TIME,'  ', HORSE_POWER );
  WRITELN( FVST, TOTAL_TIME,'  ', FORCE );
  WRITELN( VVST, TOTAL_TIME,'  ', VEL_CYL_2 );
  WRITELN( AVST, TOTAL_TIME,'  ', ACCELERATION_L );
  WRITELN( PVST, TOTAL_TIME,'  ', PRESSURE ); *)
```

```
      COUNT:=0

      END; (* IF COUNT > 1 *)

    COUNT := COUNT + 1;

    IF KEYBUFFER^.SIZE > 0 THEN
      BEGIN
      KEYBUFOPS( KCLEAR , BUFFER );
      THETA := 5;
      RUN_AGAIN := FALSE
    END

  END (* WHILE LOOP FOR THETA > ANGLE_F_STOPS *)

END; (* PROCEDURE STAGE_1 *)


PROCEDURE STAGE_2;

   BEGIN
   Y1 := MASS * LUNAR_GRAV*A_TO_CM_XY * SIN( THETA );
   WRITELN( OUTPUT, 'Y = ', Y1 );
   Y := YBAR + (Y1 + FORCE_AVG * A_TO_CM_XY * THETA * TIME) /
        ( TOTAL_TIME * MASS* LUNAR_GRAV );
   WRITELN( OUTPUT, 'Y = ', Y );
```

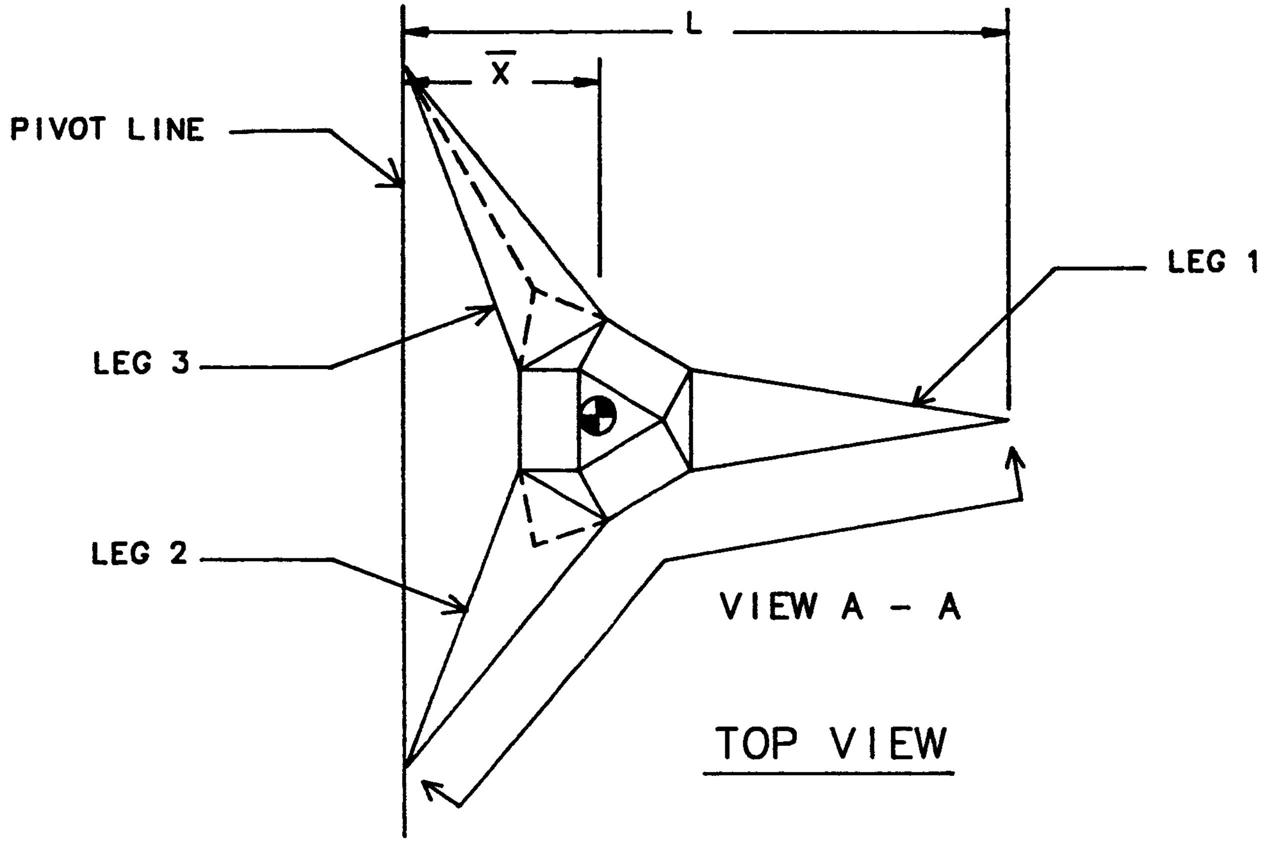
```
   X := Y / A_TO_CM_XY;
   WRITELN( OUTPUT, 'TOTAL TIME = ', TOTAL_TIME );
   WRITELN( OUTPUT, 'AVG FORCE = ', FORCE_AVG * TIME/ TOTAL_TIME );

   IF X >= 1.0 THEN
      WRITELN( OUTPUT, 'SKITTER WILL TIP OVER!!!!!!!!!' )
   ELSE
      BEGIN
      CM_ANGULAR_POSITION := ARCTAN( X / ( SQRT( 1.0 - SQR( X ))));
      WRITELN( OUTPUT, 'CM ANGULAR POSITION = ', CM_ANGULAR_POSITION*
      180/PI )
      END (* IF STATEMENT *)

END; (* STAGE 2 *)

BEGIN

RUN_AGAIN := TRUE;
INITVAR;

(* REWRITE(HPVST,'#16:HPVST');
REWRITE(FVST,'#18:FVST');
REWRITE(VVST,'#19:VVST');
REWRITE(AVST,'#20:AVST');
REWRITE(PVST,'#21:PVST'); *)
```

TABLE 1 - CENTER OF MASS AND MOMENT OF INERTIA

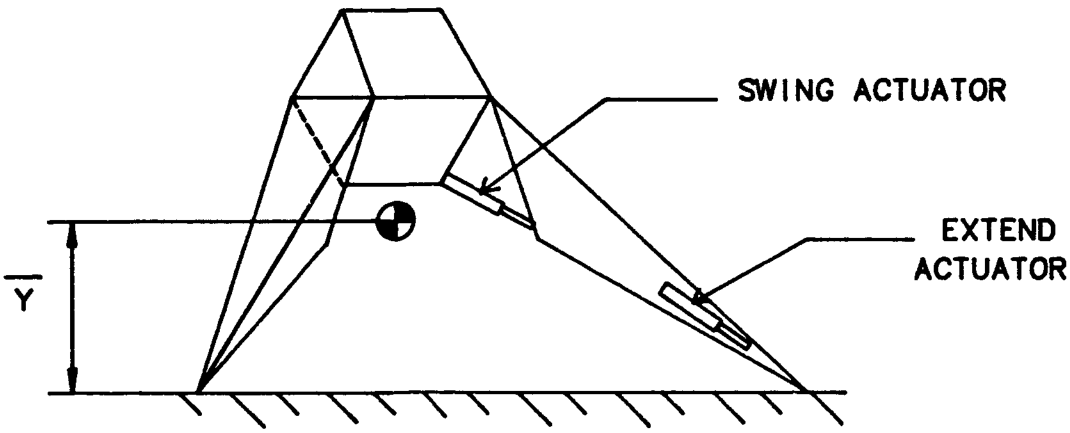
STRUCTURE	CENTER OF MASS			VOLUME
	$\bar{X}$	$\bar{Y}$	$\bar{Z}$	
LEG 1	-4.34	12.43	7.57	104.1
LEG 2	-4.34	12.43	-7.51	104.1
LEG 3	8.68	18.09	0.0	104.1
BODY	0.0	18.09	0.0	514.4
SKITTER	0.0	15.95	0.0	826.7

I = 8301 ABOUT THE CENTER OF MASS

GENERAL OVER VIEW



TOP VIEW

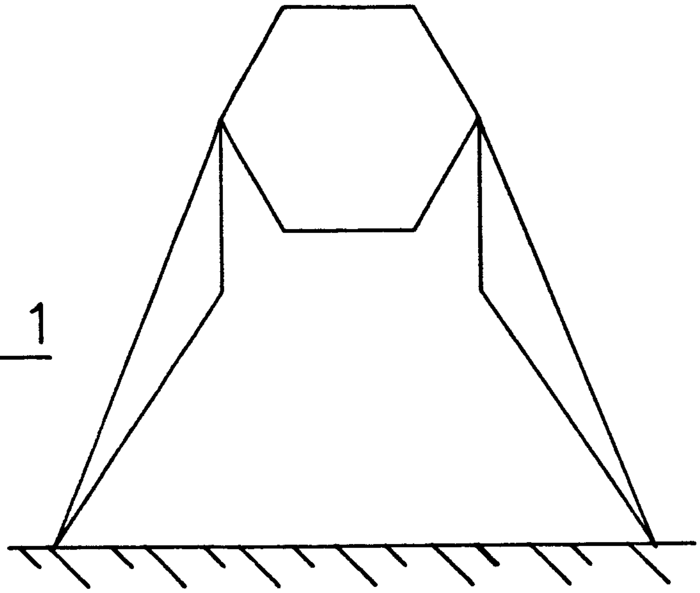


SIDE VIEW

FIGURE 1

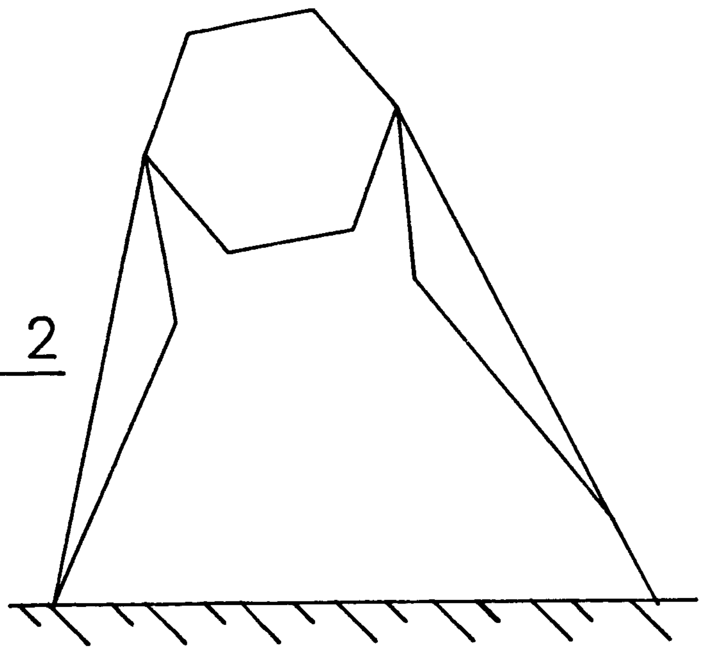
LEANING

STEP 1



EQUILIBRIUM POSITION

STEP 2



FIRST LEG EXTENDED POSITION

FIGURE 2

SQUAT

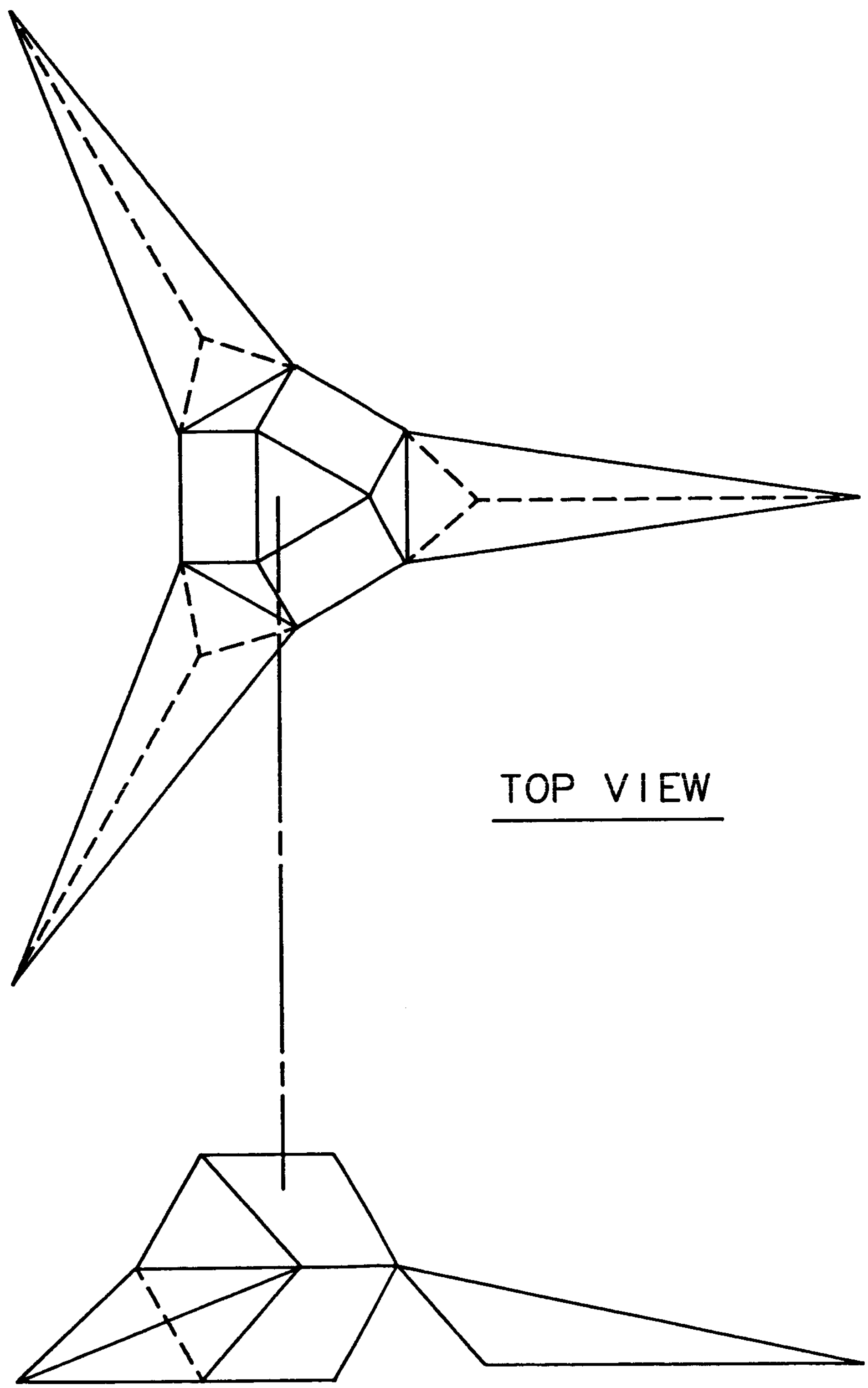


FIGURE 3

ACTUATOR CONTROL

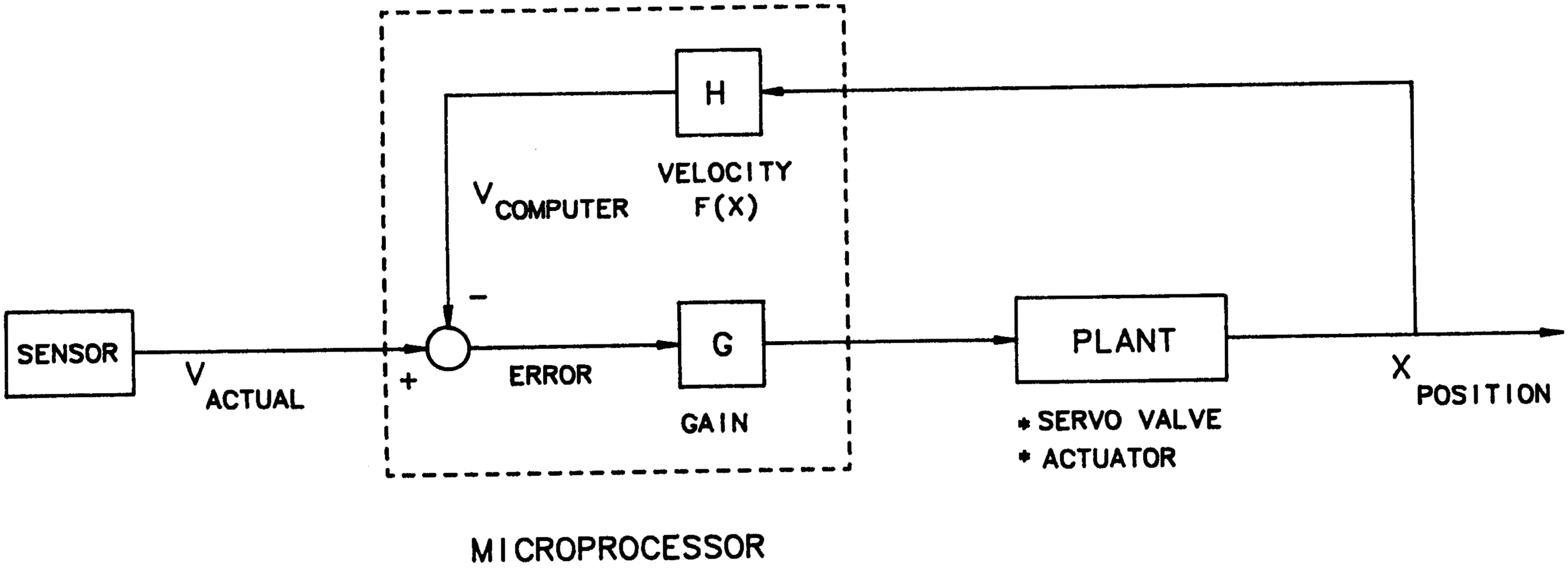
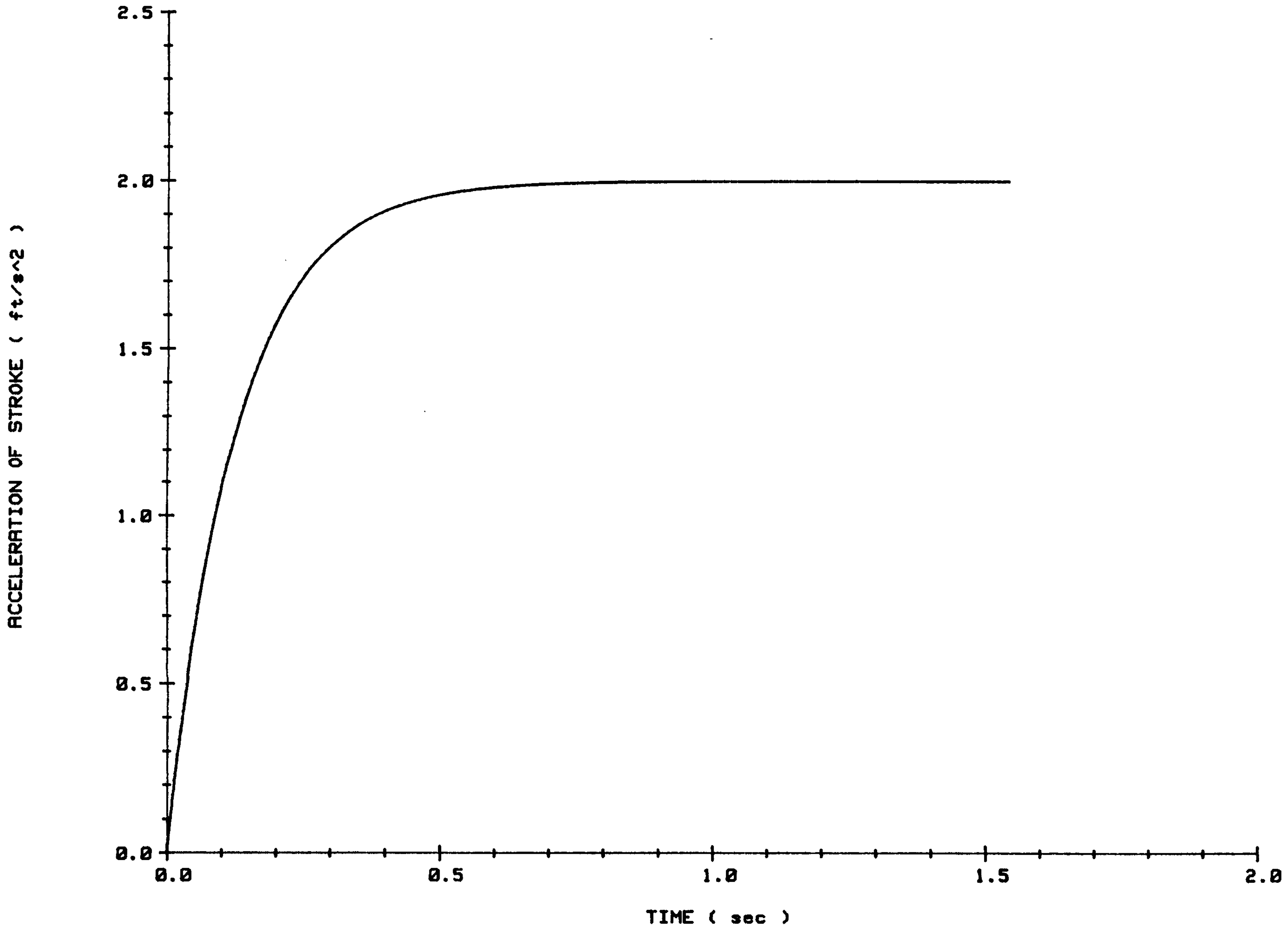
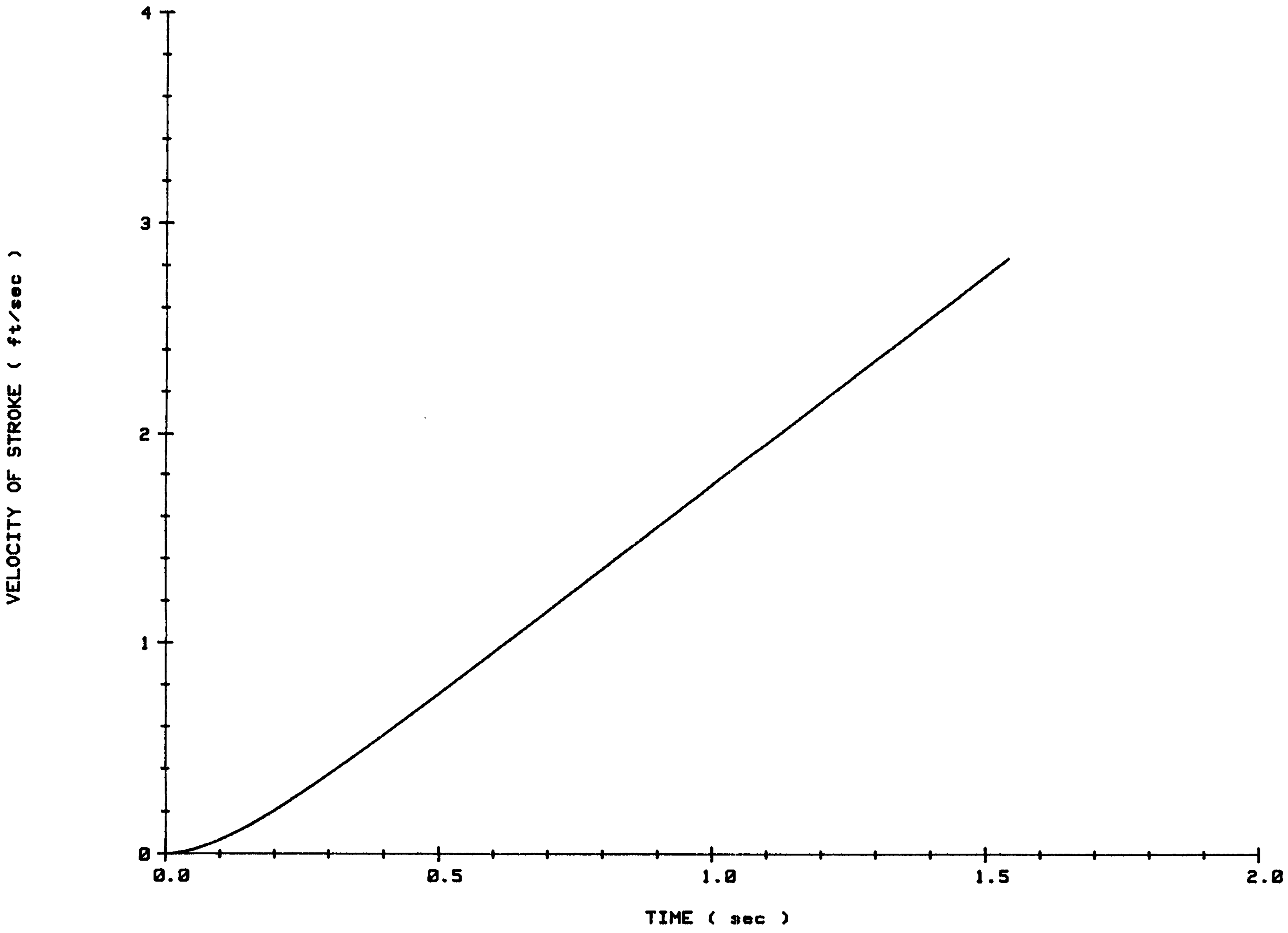


FIGURE 9

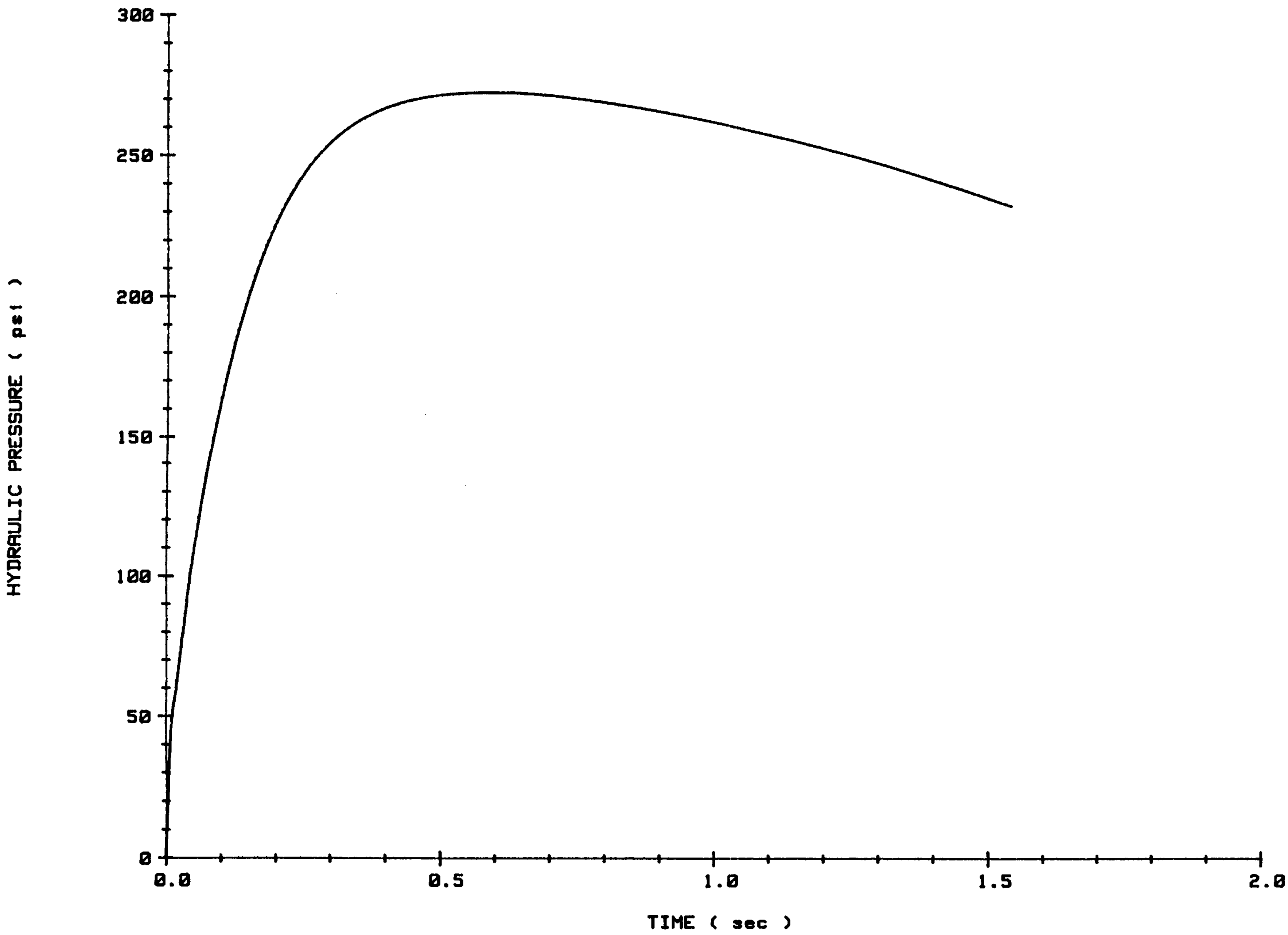
ACCELERATION OF STROKE vs. TIME
FIGURE 10



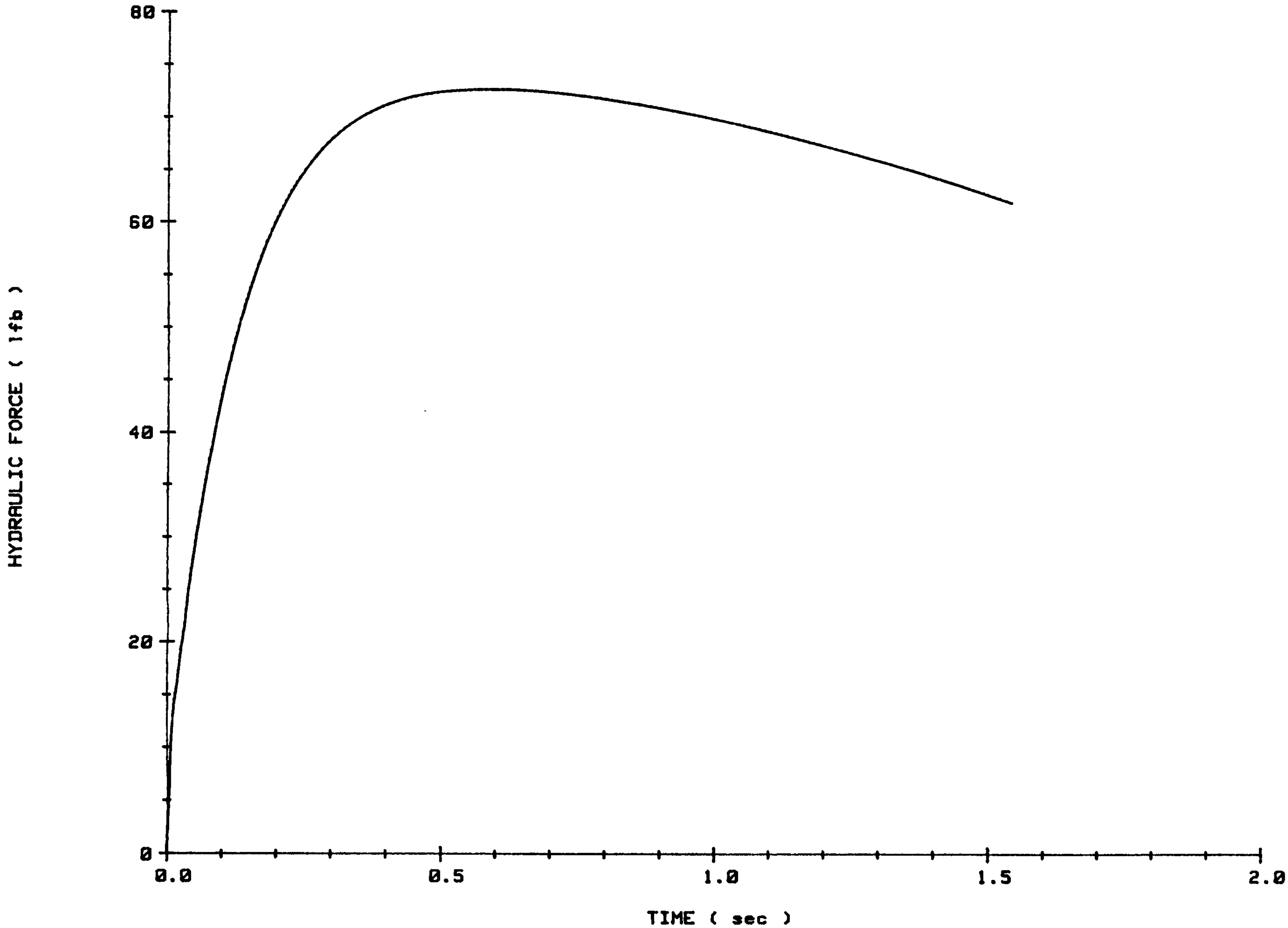
VELOCITY OF STROKE vs. TIME
FIGURE 11



HYDRAULIC PRESSURE vs. TIME
FIGURE 13



HYDRAULIC FORCE vs. TIME
FIGURE 12

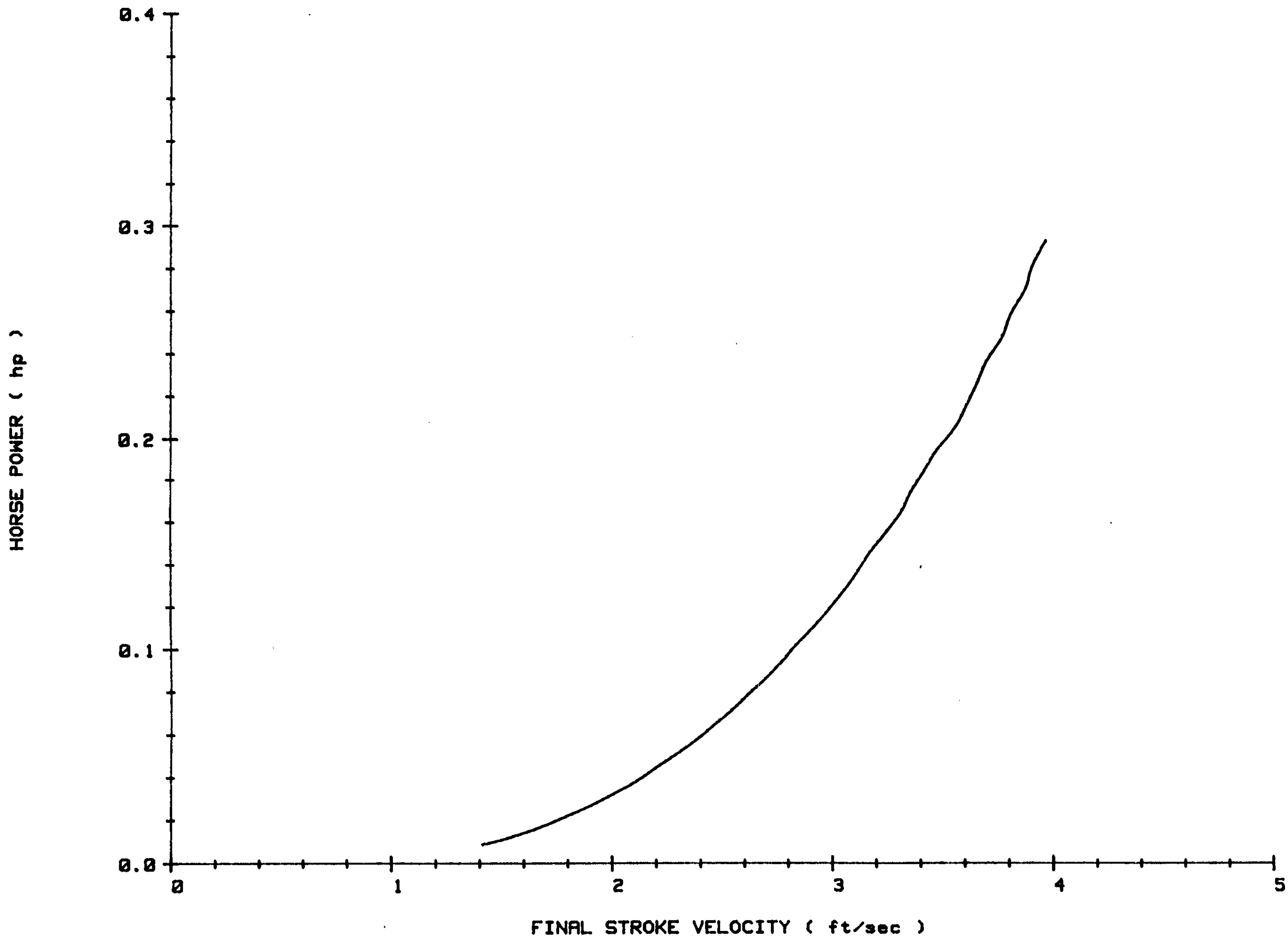


calculates an initial center of mass acceleration and rotation acceleration around the Pivot Line. These values are input to a procedure which simulates the plant of the system by utilizing the dynamics of SKITTER. A new velocity and position are calculated. This velocity is compared to the users desired velocity at that postion to generate an error signal. After this error is properily conditioned, the signal will result in a change of flow by the servo-valve which results in a new actuator motion.

A sample of the output for an input force of 20 lbf, gain of .02, and acceleration desired of 1.9 are shown in Figs. 10 - 14.

All graphs show the expected results for this particular motion. The acceleration converges to the user defined acceleration of 1.9 ft/sec^2 in only 0.4 seconds. The velocity profile is linear, as expected since the user inputs a constant acceleration to follow. The pressure is non-linear as is the force which undergoes a non-linear transformation as it rotates and maintains a constant linear acceleration for the actuator. The horse power curve also came out as expected. The low values of horse power are due to calculating the incremental change in pressure and flow to keep SKITTER moving in the prescribed motion.

HORSE POWER vs.FINAL STROKE VELOCITY
FIGURE 15



HORSE POWER vs. TIME
FIGURE 14